AE-9/AP-9 Trapped Radiation and Plasma Models

Requirements Specification

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1. Purpose and Scope

The radiation belts and plasma in the Earth's magnetosphere pose hazards to satellite systems which restrict design and orbit options with a resultant impact on mission performance and cost. For decades the standard space environment specification used by the engineering community has been provided by the NASA AE-8 and AP-8 trapped radiation belt models. There are well-known limitations on their validity, however, and a consensus has been growing among satellite engineers that a new standard trapped radiation and plasma model is needed for modern spacecraft design and mission planning purposes. This document captures the requirements for an improved radiation and plasma model, denoted AE-9/AP-9, which have been established by extensive canvassing of the satellite design community by direct conversation, email solicitation, and talks and discussion forums at workshops and conferences and over a multi-year period. Requirements will be specified in terms of the ranges, resolutions and statistical measures needed for satisfactory spectral, temporal and spatial coverage to include estimations of uncertainty in specified quantities. Excluded from consideration will be solar energetic particles and cosmic rays. These populations certainly affect spacecraft however the effort to develop models acceptable to satellite engineers has kept better pace with requirements over the last several solar cycles [e.g. *Feynman, et al.,* 1993; *Xapsos, et al.,* 2004, *Adams,* 1986; *Tylka, et al.,* 1997] .

2. Background

Since the launch of simple Geiger counters into space on the first Explorer satellites in 1958 and the subsequent discovery of the Van Allen radiation belts, there have been ongoing efforts to model the space radiation environment. These efforts were – and still are - driven not only by scientific curiosity, but by the practical need of engineers to better understand and mitigate the significant radiation hazards to spacecraft performance and survivability. Many anomaly resolution reports and several scientific studies have shown that there is a direct association between the dynamic radiation environment and system or sub-system performance [e.g. *Wrenn and Sims*, 1996; *Koons, et al.,* 2000; *Brautigam*, 2002]. Spacecraft systems and discrete component performance may gradually deteriorate with accumulative dose or may experience abrupt failure (temporary or permanent) due to discrete events associated with Single Event Effects (SEEs) or electrostatic discharge. The radiation environment specification which system engineers design to is a critical factor driving capability versus survivability tradeoffs. Spacecraft flown in orbits where a more severe radiation environment is anticipated require more expensive radiation hardened components and/or greater shielding mass which constrain launch options, limit performance and drive costs higher. Table 1 summarizes the major space particle effects on spacecraft, energy ranges of concern and time scales for natural variation.

The first definitive empirical models of the radiation belts were sponsored by the National Aeronautics and Space Administration (NASA) and developed in the 1960s and 1970s to represent the average radiation environment during the minimum and maximum phase of the solar cycle. They have been incrementally updated since then; the most recent proton and electron models being AP-8 and AE-8, respectively [*Sawyer and Vette,* 1976, *Vette*, 1991a, 1991b; see *Fung*, 1996 for a review]. These radiation belt models are still widely used, having enjoyed close to three decades as industry's *de facto* standard. However, a number of studies have been accomplished documenting the differences between the NASA models and more recent data [for example, *Gussenhoven, et al.*, 1994; *Fung,* 1996; Daly*, et al.,* 1996; *Armstrong and Colborn,* 2000; *Fennel, et al.,* 2003; *Brautigam, et al.,* 2004]. Known discrepancies include (a) over-prediction of dose for geosynchronous orbits (GEO) and highly elliptical orbits (HEO); (b) under-prediction of dose for orbits in the "slot region", i.e. low inclination orbits between about 6000-12000 km, especially dose due to long-lived higher energy protons (> 40 MeV) and electrons (> 1 MeV) injected during geomagnetic storms; and (c) no coverage of the hot and cold plasma populations below 0.1 MeV. In addition, the models give a single number representing the flux for either solar maximum (AP-8/AE-8 max) or minimum (AP-8/AE-8 min) conditions.

Environmental Hazard	**Particle Population**	**Natural Variation**
Surface Charging	0.01 - 100 keV e^-	Minutes
Surface Dose	0.5 - 100 keV e^-, H^+, O^+	Minutes
Internal Charging	100 keV - 10 MeV e^-	Hours
Total Ionizing Dose	>100 keV H^+, e^-	Hours
Single Event Effects	>10 MeV/amu H^+, Heavy ions	Days
Displacement Damage	>10 MeV H^+, Secondary neutrons	Days
Nuclear Activation	>50 MeV H^+, Secondary neutrons	Weeks

Table 1. Space particle hazards to satellite systems, approximate energy ranges of concern and timescales for natural variation. Adapted from Table 1 in *O'Brien, et al.* [2007].

A broad consensus has been building over the past decade among both engineers and scientists that a more accurate, comprehensive, and up-to-date space radiation environment model is needed. Modern design and systems engineering techniques require models with error bars, finite-time duration probability distributions, and a larger energy range, especially as increasingly complex technologies are flown and missions are being considered for non-traditional orbit regimes. There have been a number of efforts to develop new radiation belt models using data acquired onboard the CRRES [*Gussenhoven, et al.*, 1993; *Meffert and Gussenhoven*, 1994; *Brautigam, et al.*, 1992; *Brautigam and Bell*, 1995] , NOAA/TIROS [*Huston, et al*, 1996; *Huston*, 2002]], SAMPEX [*Heynderickx, et al.*, 1999], Polar [*Roeder, et al.*, 2006] , LANL and DTRS [*Boscher, et al.*, 2003, *Sicard-Piet, et al.*, 2008] satellites. These more recent models are improvements but are limited in either energy range, spatial range (e.g., exclusively at GEO or low-Earth orbit (LEO)), temporal range (e.g. limited to a small portion of the solar cycle), statistical description and specification of uncertainty, or more typically all of the above. Although newer individual models may be better for the parameter range to which they apply, it is likely that the NASA models will remain the industry standard until the space physics community develops a single, comprehensive and engineer-friendly replacement model with increased functionality addressing the known deficiencies. Any such new model must also be recognized as a standard with the requisite approval by the relevant scientific, industry and government organizations.

In 1995 an international workshop entitled “Radiation Belts: Models and Standards” was held in Brussels to begin to address the numerous scientific, engineering, and political challenges involved in developing a new standard model [*Lemaire, et al.*, 1996]. The following year the international Committee on Space Research (COSPAR) Bureau created the Panel on Standard Radiation Belts (PSRB) at its 31st Scientific Assembly in Birmingham, UK, to provide a forum for further discussion and development of such a model [*COSPAR PSRB*, 1999].

More recently, the Space Technology Alliance (STA), a group of United States government agencies to include NASA, the Department of Defense (DoD), the National Oceanic and Atmospheric Administration (NOAA), and the Department of Energy (DoE), established the Space Environmental Effects Working Group (SEEWG) to plan and coordinate research and development activities aimed at understanding and mitigating space environment effects on satellite systems. In a series of annual workshops from 2002-2006 the SEEWG brought satellite engineers, scientists and managers together to discuss space environmental impacts on specific technological systems. The highest priority recommendation coming out of the first workshop (SEEWG 2002, “Space Environment Effects on Large Imaging Systems”) and reinforced at every workshop thereafter was to "create a technical committee to develop updated radiation environment models". This recommendation arose from the frustration of satellite builders knowing that the AP-8 and AE-8 models were inaccurate but being forced to use them because they are the accepted industry standard written into system requirements documents.

Following the SEEWG recommendations, a multi-agency steering committee was formed by NASA, the Air Force Research Laboratory, Aerospace Corporation, the Naval Research Laboratory and the European Space Agency with the charge of creating a roadmap for a new standard model development effort. With sponsorship from NASA's Living with a Star (LWS) program, a Working Group Meeting on New Standard Radiation Belt and Space Plasma Models for Spacecraft Engineering was organized and held on 5-8 October 2004 (hereafter referred to as the "NASA workshop"). Scientists and model users were well represented, with international participation by interested parties from industry, academia, national laboratories, and other government agencies. Industry representatives came up with a detailed list of requirements [*Industry User's Group*, 2004] and a summary of the entire workshop proceedings is provided by *Lauenstein, et al.* [2005]. After the workshop the COSPAR Panel for Radiation Belt Environment Modeling (PRBEM, formerly the PSRB) submitted a proposal to the COSPAR Bureau in March 2005, which was consequently accepted, concerning the development of a new international standard radiation belt model with the aim to "create an international group of expert[s] well distributed around the world to set up a common framework for everybody involved in this field". A document summarizing user's needs has been produced [*Bourdarie, et al., 2005*] and is based largely on the discussions at the LWS Workshop.

To meet satellite design needs the National Reconnaissance Office (NRO), the Air Force Research Laboratory (AFRL), the Aerospace Corporation, Los Alamos National Laboratory (LANL) and the Naval Research Laboratory (NRL) formed a partnership in 2006 to produce an improved version of the trapped radiation belt and plasma models, hereafter denoted AE-9 and AP-9 for electrons and protons, respectively. Continuation of the requirements dialogue with the space engineering community was and continues to be a priority. Communication has included a presentation and round-table discussion at the 2007 Space Weather Workshop, a presentation and industry side-bar session at the 2008 GOMACTech Meeting, distribution of flyers soliciting feedback at the 2007 IEEE Nuclear and Space Radiation Effects Conference (NSREC) and an email sent to the attendance lists from SEEWG and NSREC meetings requesting inputs on requirements. In addition, information has been provided by contacts within the satellite industry who have worked directly with Aerospace and AFRL on the design and construction of specific satellites. A web-based forum was established and continues to operate (lws-set.gsfc.nasa.gov/RadSpecsForum.htm) to further solicit feedback. The AE-9/AP-9 team has compiled the requirements presented in the next section by sorting, integrating and prioritizing the information gathered from all the activities mentioned above.

3. Requirements

The goal of the AE-9/AP-9 model is to provide an accurate statistical description of the trapped radiation and plasma environment suitable for spacecraft design applications. Requirements will be specified in terms of what the end product should be capable of, not what is actually needed to build the model, e.g. the amount and quality of satellite data or the type of interpolation algorithms. Due to known data gaps and incomplete physics-based models it is impossible to build an AP-9/AE-9 model satisfying all the requirements at this time. A spiral development approach has been adopted whereby a sequence of versions will be produced as more data is gathered and algorithms defined with each version a significant improvement on the last and another step close to meeting the complete requirements as defined in this document.

Priorities for the development spiral of AE-9/AP-9 in terms of the particle population, energy range and location as deduced from the satellite design community input are summarized in Table 2. Location is given as an orbit range, i.e. low-Earth orbit (LEO), range 200 km -2000 km; medium-Earth orbit (MEO), range 2000- 35,000 km; geosynchronous orbit (GEO), range 35,000 – 37,000 km with near 0 degrees inclination; and highly elliptical orbit (HEO), range 400 km (perigee) – 46,000 km (apogee). The primary quantity to be specified is the omni-directional particle flux *j* in units of #/(cm^2 sec MeV) for high energy electrons and protons and #/(cm^2 sec keV) for the plasma. Specific energy, spatial and temporal resolution is given in Tables 3a and 3b for high-altitude (1500 km – 48000 km) and low-altitude (200 km – 1500 km) domains of the model, respectively. The reasoning behind the specifications is discussed in the sections below.

Priority	Population	Energy	Location
1	Protons	>10 MeV (> 80 MeV)	LEO & MEO
2	Electrons	> 1 MeV	LEO, MEO & GEO
3	Plasma	30 eV – 100 keV (30 eV – 5 keV)	LEO, MEO, HEO & GEO
4	Electrons	100 keV – 1 MeV	MEO & GEO
5	Protons	0.1 MeV – 10 MeV (5 – 10 MeV)	LEO, MEO & GEO

Table 2. Prioritized requirements for the AE-9/AP-9 model in terms of population, energy range, and orbital location .

a. Energy Range and Resolution

Not surprisingly, given their role in limiting system lifetimes by means of total dose and displacement damage, energetic protons (10 - 500 MeV) and electrons (> 1 MeV) in the inner magnetosphere (LEO & MEO) are the top priorities. Models of the poorly characterized lower energy plasma environment (< 10 keV) were a high priority considering the large surface areas, novel materials and coatings under consideration for use in future space systems. The term "plasma" includes electrons, protons (i.e. singly charged hydrogen, or H^+) and singly charged oxygen (O^+). Better characterization of the dynamic medium-energy electrons (> 0.1 MeV) in the slot and outer zone (6000 - 36000 km altitude) was also universally recognized as important for improving designs to withstand deep charging events. Medium energy protons (1 -10 MeV) which can cause dose degradation of solar panels, for example, and are not yet adequately specified.

The resolution in energy is influenced by the degree of structure created by natural processes within specific spectral ranges [e.g., *O'Brien et al.*, 2007]. At lower energies there can be peaked structures [e.g. *Roderer et al.*, 2005] requiring a resolution of 10 logarithmically spaced intervals per decade for adequate specification. At the highest energies spectra drop off monotonically and a resolution of 5 logarithmic intervals/decade is sufficient. For electrons and protons the break point energy to go from higher to lower resolution is taken to be 3 MeV and 1 MeV, respectively. A relatively high value is chosen for the electrons since there is evidence in satellite data of peaks in the spectrum up to ~ 2 MeV [*Vampola,* 1972; *Friedel,* 2007; *Brautigam,* 2007.]

Pop.	**Energy Range**	**Energy Res. (bins/dec.)**	**⊥ B Res. Radial (Re)**	**⊥ B Res. Azimuth (deg)**	**|| B Res. Pitch-angle (deg)**	**Flux Average Periods**
Protons	1.0 MeV – 2.0 GeV	5	0.1	N/A	10	Mission
	0.3 – 1.0 MeV	10				
Electrons	3.0 – 30.0 MeV	5	0.05	N/A	10	5 min, 1 hr, 1 day, 1 wk & mission
	0.3 – 3.0 MeV	10				
Plasma	30.0 eV - 0.3 MeV	10	0.5	15	10	5 min, 1 hr, 1 day, 1 wk & mission

Table 3a. Specific energy, spatial and temporal resolution requirements for the spatial range 1500 km – 48000 km. See text for details.

Pop.	**Energy Range**	**Energy Res. (bins/dec.)**	**Alt. Res. (km)**	**Lat. Res. (deg)**	**Lon. Res. (deg)**	**Flux Average Periods**
Protons	1.0 MeV – 2.0 GeV	5	50	3	3	Mission
	0.3 – 1.0 MeV	10	25 (< 300)			
Electrons	3.0 – 30.0 MeV	5	50	3	3	5 min, 1 hr, 1 day, 1 wk & mission
	0.3 – 3.0 MeV	10				
Plasma	30.0 eV - 0.3 MeV	10	500	2 (< 60^o mlat) 1 (> 60^o mlat)	7	5 min, 1 hr, 1 day, 1 wk & mission

Table 3b. Specific energy, spatial and temporal resolution requirements for the spatial range 200 km – 1500 km. The altitude resolution in brackets for protons is for altitudes < 300 km. Different values of latitude resolution for the plasma are given for less than and greater than 60 degrees magnetic latitude. See text for details.

b. Temporal Range and Resolution

Design lifetimes for a satellite can last from months to well over a decade. A complete radiation and plasma model must therefore accurately capture the statistics of the natural dynamics of the space particle populations as they vary over the course of an 11 year solar cycle. A solar cycle phase dependence will not be included in AE-9/AP-9, at least in the initial versions. The challenge of doing so is formidable, as discussed later in this section, and omitting it might not be an unreasonable sacrifice. Satellite development and launch schedules frequently slip, on-orbit lifetimes are often planned for 10 years or more, and there are large uncertainties in predicting the phase and intensity of future solar cycles. Prudent satellite builders should consider statistics from the complete solar cycle to ensure survivability.

Of critical importance are the periods of time for which statistical distributions of the average flux over that time are needed. Hereafter these periods will be denoted as “flux-average periods” and are defined in terms of the time scales relevant to specific satellite effects rather than natural variation. For example, in the case of internal spacecraft charging it takes a finite time for charge deposited by energetic electrons to build up to critical levels where dielectric breakdown occurs. The timescale is a complex function of geometry, shielding, component material properties and impinging flux level. A meaningful analysis of breakdown probability and the consequent damage to the satellite requires the knowledge of the flux statistics averaged over a number of different time periods. Specific flux-average periods of 5 min, 1 hour, 1 day, 1 week and the mission duration are the consensus values deemed to be sufficient for design purposes. Mission aggregated quantities, for example the total fluence at a given energy, can be obtained by multiplying the mission duration flux-average by the mission period. Column six in Table 3 lists the required flux-average periods for the given particle populations.

It is worth noting that the requirements for capturing solar cycle variation and different flux-average periods are a major design driver for AE-9/AP-9. Determination of such statistics for an arbitrary near-Earth orbit requires knowledge of the temporal correlations over the period of concern along the orbit trajectory. Such knowledge is difficult to ascertain from a purely empirical approach to model construction, whereby data taken at different times in a solar cycle from a relatively few number of satellites in narrow orbit regimes is binned and mapped in magnetic coordinates. Initial versions of AE-9/AP-9 will be limited in their description of the solar cycle variation and accommodation of different flux-average periods. Full capability will be obtained in later versions by employing reanalysis methods to create statistically correct “standard solar cycle” particle flux maps in which user’s can propagate an arbitrary orbit and obtain the desired flux-average period distributions in a Monte-Carlo fashion. The reanalysis techniques use physics-based data assimilative models which are still in the preliminary phases of development. Such models also need detailed validation to quantify the uncertainties and in some regimes, e.g. high-energy protons in the inner belt, appropriate measurements have not yet been made.

c. Spatial Range and Resolution

The spatial range of AE-9/AP-9 will be from 200 – 48,000 km in altitude at all latitudes in order to cover the near-Earth orbital regimes listed in Table 2. Trapped energetic particles and plasma are not uniformly spread throughout this region and for the most part are at the lower latitudes. For example, trapped energetic protons lie between 200 – 6000 km at latitudes less than 45 degrees. Perhaps the most spatially pervasive population is the plasma which can extend from the outer boundaries to ~ 6000 km at low latitudes and down to several hundred kilometers at higher latitudes, the latter in the form of precipitating aurora.

Spatial resolution is dictated by the characteristic scale lengths for variations in the particle distributions. Charged particle motion in near-Earth space is strongly influenced by the Earth's magnetic field and gradients in the distribution functions are best represented in directions parallel and perpendicular to the field lines. An exception to this is at lower altitudes where effects due to atmospheric neutral density and the non-dipole components of the Earth's magnetic field can produce steeper gradients then at higher altitudes. In this case the traditional altitude, latitude and longitude is sufficient. The cutoff between high and low altitude resolution is taken to be 1500 km - slightly above the 1200 km altitude where neutral density effects begin to effect high-energy proton distributions [e.g., *Ginet, et al.,* 2007.]

Considering the higher altitude regime, variations of particle distributions along the magnetic field lines correspond closely to the variation in equatorial pitch-angle distribution [e.g. *Roederer*, 1970], a quantity which can be measured from a single spacecraft. Detailed pitch-angle measurements, however, are more difficult to make than omni-directional measurements with consequently fewer reported results. Examining the data which is available, e.g. *Vampola,* 1996; *Gussenhoven, et al.*, 1993; *Roeder, et al.,* 2005, for energetic electrons, energetic protons and plasma, respectively, a resolution of 10 degrees (as shown in Table 3a) appears sufficient to capture the variations relevant for spacecraft engineering.

Scale lengths radially perpendicular to the magnetic field ($h_\perp$) for representative samples of energetic electron, proton and plasma populations are summarized in Table 4. These scale lengths have been estimated in regions of the strongest gradients (see Description column) at the locations quantified by the magnetic L parameter (approximately the distance from the center of the Earth to a magnetic field line at the magnetic equator) using the empirical results reported in *Brautigam, et al.* [1992], *Gussenhoven, et al.* [1993], and *Sheldon and Hamilton* [1993] for the energetic electrons, protons and plasma, respectively. The values of $h_\perp$ are not strongly dependent on energy for a given population and form the basis for the entries in column 4 of Table 3a.

In the azimuth direction perpendicular to the magnetic field the higher energy electron and proton populations are distributed symmetrically due to the insensitivity of their drift motion to magnetospheric electric fields. Implementation of this symmetry depends on the details of the magnetic coordinates and data binning algorithms used in developing the model. Algorithms for the transformation and inverse transformation between the magnetic coordinates related to particle motion and the physical coordinates required for engineering analysis will be a necessary component of AE-9/AP-9. The motion of the lower energy plasma population is sensitive to the large scale electric fields and produces significant variation in azimuth. A resolution of 15 degrees, or 1 hour in local-time, is consistent with other plasma models [*Roeder, et al.,* 2005; *O'Brien and Lemon,* 2007] and should be sufficient for satellite design purposes.

Population	L (Re)	$h_\perp$ (Re)	Description
2.0 MeV electrons	2.75	0.40	Flux on inner slope of outer zone
	5.75	0.91	Flux on outer slope of outer zone
57 MeV protons	1.2	0.036	Flux on inner slope of inner zone
	2.5	0.11	Flux on outer slope of inner zone
1- 300 keV H^+	2.5	1.5	Density on inner slope of ring current region
	6.	10.	Density in plasma sheet
1- 300 keV O^+	3.5	0.8	Density on inner slope of ring current region
	5.5	1.25	Density on outer slope of ring current region

Table 4. Characteristic scale lengths for directions perpendicular ($h_\perp$) and parallel ($s_\parallel$) to the magnetic field for representative energetic particle and plasma populations in the magnetosphere. Values are shown for magnetic L-shell parameters corresponding to regions of the strongest gradients. All units are in Earth radii (Re).

At altitudes below approximately 1200 km effects of the neutral density become important for the energetic protons and the resolution needed to accurately resolve is driven by the density scale height. Data shows that a vertical resolution of 50 km and horizontal resolution of 3 degrees in latitude and longitude (~330 km) is good for altitudes 400 – 1500 km [e.g. *Ginet et al.,* 2007] and should be sufficient down to 300 km where the density scale height drops to ~50 km [*Jacchia,* 1977]. A resolution of 25 km in altitude should be good between 200-300 km where the density scale height drops from 50 km to ~30 km. Preliminary studies of energetic electron distributions between 400 – 1700 km [*Perry et al.,* 2008] show steep gradients due to the non-dipole nature of the Earth's field producing north-south asymmetries when pitch-angle distributions near the angles where particles are lost due to neutral density effects are mapped to physical locations along field lines. The study indicates a model resolution equivalent to that of protons is sufficient.

Unlike the energetic particles the altitude dependence of the plasma distribution at low altitudes is weakly dependent on neutral density until below 200 km. However, there is detailed structure in the horizontal distribution of the aurora at high latitudes. Standard climatological models of the aurora [e.g. *Hardy et al.,* 1987; *Hardy et al.,* 1991] use a resolution of approximately 7 degrees in magnetic longitude, 2 degrees between 50 - 60 degrees and 1 degree above 60 degrees magnetic latitude. These values are adopted for AE-9/AP-9.

d. Directionality

The specification of an omni-directional flux value at each point in the spatial domain when combined with a magnetic field model will allow for the determination of the local pitch-angle distributions. These define the angular dependence of the flux arriving at a spacecraft in directions perpendicular to the local magnetic field with an assumed symmetry about the field direction. Algorithms to convert omni-directional to local pitch angle fluxes and an adequate magnetic field model are requirements for AE-9/AP-9. Angular resolution will be equivalent to that used in determining the spatial resolution parallel to the magnetic field as discussed in Sec 3.c, i.e. 10 degrees.

The assumption of symmetry of the angular distribution about the magnetic field breaks down for energetic protons at the altitudes where the cyclotron radius becomes of order or greater than the density scale height. Known as the "East-West Effect" the asymmetry is a result of the differing scattering rates encountered along different cyclotron paths corresponding to the same pitch-angle. Becoming noticeable at 1200 km, the effect increases rapidly below 1000 km and can result in a factor of approximately two in intensity at altitudes below 800 km. Fortunately, a formula has been developed expressing the relative intensity of flux in a given direction [*Lencheck and Singer*, 1962] and it has been shown to be reasonably accurate over the altitude range 400 – 1700 km [*Ginet et al.*, 2007] . AE-9/AP-9 will incorporate this formula in the low-altitude regime to provide directional information about the axis of the magnetic field direction given the local pitch-angle distributions and the magnetic field model.

e. Statistical Specification

The primary function of the AE-9/AP-9 model is to provide information on the probability of encountering certain levels of flux over the course of a satellite mission. In particular the satellite design community has communicated that the average, 50th percentile (median), 75th percentile and 95th percentile values of the omni-directional flux for each flux-average period are key quantities required for arbitrary orbits and mission durations .

The AE-9/AP-9 models will be capable of providing percentiles of quantities aggregated over the mission (e.g., total fluence) and over the flux-average periods (e.g., 5-minute averaged flux). The nth percentile aggregate or worst case will indicate the threshold not exceeded in n percent of missions. Thus, designing to the 95th percentile accepts a 5 percent chance that the environment will exceed the specification before the end of the design life. These percentiles will account for variations due to geophysical processes, uncertainties in the modeling methods and the measurement errors carried through from the original observations on which AE-9/AP-9 is built.

Input to AE-9/AP-9 should be the orbital elements, start time and mission duration. Though the model will be comprised of different components working together to accomplish the sophisticated mapping and interpolation involved in achieving the required statistics and resolution from the limited data sets and physics-based models, it will all be wrapped in a simple, user-friendly application.

4. Acknowledgements

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5. References

Adams, J.H.,Jr. "Cosmic Ray Effects on Micro-Electronics (CREME), Part IV" , Naval Research Laboratory Memorandum Report 5901, December 31, 1986.

Armstrong, T.W. and B.L. Colborn, Evaluation of Trapped Radiation Model Uncertainties for Spacecraft Design, *NASA/CR-2000-210072*, 2000.

Boscher, D.M., S.A. Bourdarie, R.H.W. Friedel, and R.D. Belian , Model for Geostationary Electron Environment: POLE, *IEEE Trans. Nucl. Sci., 50*, 2278-2283, 2003.

Bourdarie, S., B. Blake, J. B. Cao, R. Friedel, Y. Miyoshi, M. Panasyuk and C. Underwood, User's Needs, V1.2, available at Committee on Space Research (COSPAR) Panel for Radiation Belt Environment Modeling (PRBEM) Reference Documents website, http://wwwe.onecert.fr/craterre/prbem/home.html , 2005.

Brautigam, D.H. and J. Bell, CRRESELE Documentation, *PL-TR-95-2128,* ADA 301770, Air Force Research Laboratory, Hanscom AFB, MA, 1995.

Brautigam, D.H., M.S. Gussenhoven, and E.G. Mullen, Quasi-static Model of Outer Zone Electrons, *IEEE Trans. Nucl. Sci., 39*, 1797-1803, 1992.

Brautigam, D.H., CRRES in review: space weather and its effects on technology, *Journal of Atmospheric and Solar-Terrestrial Physics, 64*, 1709-1721, 2002.

Brautigam, D.H., K.P. Ray, G.P. Ginet and D. Madden, Specification of the Radiation Belt Slot Region: Comparison of the NASA AE8 Model With TSX5/CEASE Data, *IEEE Trans. Nucl. Sci., 51,* 3375-3380, 2004.

Brautigam, D. H., Spectral Inversion Challenge, presented at the Next Generation Radiation Specification Consortium, El Segundo, CA, 27 Feb - 1 Mar 2007.

Committee on Space Research (COSPAR) Panel for Radiation Belt Environment Modeling (PRBEM), information available on the world wide web at www.magnet.oma.be/psrb/home.html , 2005.

Daly, E.J., J. Lemaire, D. Heynderickx, and D.J. Rodgers, Problems with models of the radiation belts, *IEEE Trans. on Nucl. Sci*., *43*, 403-415, 1996.

Fennel, J. F., J. B. Blake, D. Heynderickx and N. Crosby, HEO Observations of the Radiation Belt Fluxes: Comparison with Model Predictions and a Source for Model Updates, *EOS Trans. AGU, 84.,* #SH52A-05, 2003.

Feynman, J., G. Spitale, J. Wang, and S. Gabriel, Interplanetary fluence model: JPL 1991, *J. Geophys. Res*., *98*, 13281-13294, 1993.

Friedel, R., GPS Data & LANL Inversion Algorithms, presented at AE(P) Model Review, Hanscom AFB, MA, 29 Nov 2007.

Fung, S.F., Recent developments in the NASA trapped radiation models, in *Radiation Belts: Models and Standards, Geophys. Monogr. Ser., 97*, edited by J.F. Lemaire, D. Heynderickz, and D.N. Baker, pp. 79-91, AGU, Washington, D.C., 1996.

Ginet, G. P., B. K. Dichter, D. H. Brautigam and D. Madden, Proton Flux Anisotropy in Low Earth Orbit, *IEEE Trans. Nucl. Sci, 54,* 1975-1980, 2007.

Gussenhoven, M.S., E.G. Mullen, M.D. Violet, C. Hein, J. Bass, and D. Madden, CRRES High Energy Proton Flux Maps, *IEEE Trans. Nucl. Sci., 40*, 1450-1457, 1993.

Gussenhoven, M.S., E.G. Mullen, and D.H. Brautigam, Near-earth radiation model deficiencies as seen on CRRES, *Adv. in Space Res., 14*, 927-941, 1994.

Hardy, D. A., M. S. Gussenhoven, R. A. Raistrick and W. McNeil, Statsitical and Functional Representations of the Pattern of Auroral Energy Flux, Number Flux and Conductivity, *J. Geophys. Res.,*, 92, 12275-12294, 1987.

Hardy, D. A., W. McNeil, M. S. Gussenhoven and D. Brautigam, A Statistical Model of Auroral Ion Precipitation 2. Functional Representation of the Average Patterns, *J. Geophys. Res.,* 96, 5539-5547, 1991.

Heynderickx, D., M. Kruglanski, V. Pierrard, J. Lemaire, M. D. Looper, and J. B. Blake, A Low Altitude Trapped Proton Model for Solar Minimum Conditions Based on SAMPEX/PET Data, *IEEE Trans. Nucl. Sci., 46,* 1475, 1999.

Huston, S.L, G.A. Kuck, and K.A. Pfitzer, Low altitude trapped radiation model using TIROS/NOAA data, in , in *Radiation Belts: Models and Standards, Geophys. Monogr. Ser., 97*, edited by J.F. Lemaire, D. Heynderickz, and D.N. Baker, pp. 119-124, AGU, Washington, D.C, 1996.

Huston, S.L., Space Environment and Effects: Trapped Proton Model, *NASA/CR-2002-211784*, NASA Marshall Spaceflight Center, Huntsville, AL, 2002.

Industry Users Group, Model Requirements Update: The Oracle has Spoken, *Working Group Meeting on New Standard Radiation Belt and Space Plasma Models for Spacecraft Engineering*, Oct 2004, College Park, MD, presentations available on the world wide web at http://lwsscience.gsfc.nasa.gov/RB_meeting1004.htm , 2004.

Koons, H.C., J.E. Mazur, R.S. Selesenick, J.B. Blake, J.F. Fennell, J.L. Roeder, and P.C. Anderson, The Impact of the Space Environment on Space Systems, in *6th Spacecraft Charging Technology Conference, AFRL Tech. Report No. AFRL-VS-TR-20001578*, pp. 7-11, Air Force Research Laboratory, Hanscom AFB, MA, 2000.

Lauenstein, J.-M., J.L. Barth, and D.G. Sibeck, Toward the development of new standard radiation belt and space plasma models for spacecraft engineering, *Space Weather*, *3*, doi:10.1029/2005SW000160. Presentations from the workshop are available on the world-wide web at http://lwsscience.gsfc.nasa.gov/RB_meeting1004.htm , 2005.

Lemaire, J.F., D. Heynderickx, and D.N. Baker, editors, *Radiation Belts: Models and Standard*, *Geophys. Monogr. Ser., 97*, 1999.

Lenchek, A. M. and S.F. Singer, Effects of the Finite Gyroradii of Geomagnetically Trapped Protons, *J. Geophys. Res., 67*, 4073-4075, 1962.

Meffert, J.D., and M.S. Gussenhoven, CRRESPRO Documentation, *PL-TR-94-2218*, ADA 284578, Phillips Laboratory, Hanscom AFB, MA, 1994.

O'Brien, T.P. and C.L. Lemon, Reanalysis of plasma measurements at geosynchronous orbit, *Space Weather*, 5, doi:10.1029/2006SW000279, 2007.

O'Brien, T.P., J.E. Mazur, J.B. Blake, M.D. Looper, J.T. Bell, G.P. Ginet and A.B. Campbell, Mapping the Inner Van Allen Belt: Requirements and Implementation Strategy, *Aerospace Report No. ATR-2006(8377)-1*, Aerospace Corporation, El Segundo, CA, 2007.

Perry, K. P., S. Quigley and G. P. Ginet, Electron Maps for LEO Using CEASE/TSX-5 Electron Data, presented at 2008 Space Weather Workshop, Boulder, CO, 29 Apr – 3 May, 2008.

Roeder, J. L., M. W. Chen, J. F. Fennell and R. Friedel, Empirical models of the low-energy plasma in the inner magnetosphere, *Space Weather,* 3, doi:10.1029/2005SW000161, 2005.

Roederer, J., *Dynamics of Geomagnetically Trapped Radiation,* Springer-Verlag, New York, 1970.

Sawyer, D.M. and J.I. Vette, AP-8 Trapped Proton Model, *NSSDC/WDC-A-R&S 76-06,* Natl. Space Sci. Data Cent., Greenbelt, MD, 1976.

Sheldon, R. B. and D. C. Hamilton, Ion Transport and Loss in the Earth's Quiet Ring Current 1. Data and Standard Model, *J. Geophys. Res.*, 98, 13491-13508, 1993.

Sicard-Piet, H. S. Boudarie, D. Boscher, R. H. W. Friedel, M. Thomsen, T. Goka, H. Matsumoto, and H. Koshiishi, A new international geostationary electron model: IGE-2006, from 1 keV to 5.2 MeV, *Space Weather,* 6, doi:10.1029/2007SW000368, 2008.

Tylka, A. J., James H. Adams, Jr., Paul R. Boberg, Buddy Brownstein, William F. Dietrich, Erwin O. Flueckiger, Edward L. Petersen, Margaret A. Shea, Don F. Smart, and Edward C. Smith, "CREME96: A Revision of the Cosmic Ray Effects on Micro-Electronics Code", IEEE Transactions on Nuclear Science, 44, 2150-2160, 1997.

Vampola, A. L., Natural Variations in the Geomagnetically Trapped Electron Population, in *Proceedings of the National Symposium on Natural and Manmade Radiation in Space,* NASA TM X-2440, E. A. Warman, ed., 539-547, 1972.

Vampola, A. L., Outer Zone Energetic Electron Environment Update, *Final Report of ESA/ESTEC/WMA/P.O. 151351,* 1996. Results are also summarized in Lemaire, J., D. Heynderickx, M. Kruglanski, A. D. Johnstone, D. J. Rodgers, S. Szita, G. Jones, E. Keppler, R. Friedel and G. Loidl, *TREND-3 Radiation Environments of Astronomy Missions and LEO Missions, Final Report*, Chapter 10., ESTEC Contracts No. 10725/94/NL/JG(SC) and 11711/95/NL/JG(SC) WO-3, 1998.

Vette, J.I., The NASA/National Space Science Data Center Trapped Radiation Environment Model Program (TREMP) (1964-1991), *NSSDC/WDC-A-R&S 91-29,* Natl. Space Sci. Data Cent., Greenbelt, MD, 1991a.

Vette, J.I., The AE-8 Trapped Electron Model Environment, *NSSDC/WDC-A-R&S 91-24,* NASA Goddard Space Flight Center, Greenbelt, MD, 1991b.

Wrenn, G.L. and A.J. Sims, Internal Charging in the Outer Zone and Operational Anomalies, in *Radiation Belts: Models and Standards*, *Geophys. Monogr. Ser., 97,* edited by J.F. Lemaire, D. Heynderickz, and D.N. Baker, pp. 275-278, AGU, Washington, D.C, 1996.

Xapsos, M.A., C. Stauffer, G.B. Gee, J.L. Barth, G. Stassinopoulos and R.E. McGuire, Model for Solar Proton Risk Assessment, *IEEE Trans. Nucl. Sci., 51*, 3394-3398, 2004.

6. Points of Contact

Comments on this document and/or feedback on specific satellite design requirements can by input to the Radiation Model User Forum website (http://lws-set.gsfc.nasa.gov/RadSpecsForum.htm) or sent to any of the individuals listed below.

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